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# **Integrated well log and 2-D seismic data interpretation to image the subsurface stratigraphy and structure in north-eastern Bornu (Chad) Basin**

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## **Abstract**

Structural and stratigraphic mapping within the Bornu Basin in north east Nigeria was commonly carried out using traditional field geological methods. However, such traditional approaches remain inadequate in the semi-arid region characterised by topographically flat areas and lack of continuous bedrock outcrops that are mostly concealed beneath sand cover. Previous studies in the north-eastern part of the basin carried out using ditch cuttings from few wells and disconnected seismic data were largely inadequate and the resulting stratigraphic analyses were more often generalised. This paper presents an integrated structural and stratigraphic study of the basin using combined subsurface geophysical datasets. A Combined Log Pattern (CLP) method is a well log analysis, which utilises various well log data including gamma ray, resistivity, bulk density and sonic logs to identify lithology and stratigraphic boundaries of subsurface formations. This method is applied to constrain the subsurface stratigraphy of the north-eastern part of the Bornu Basin bordering the Lake Chad. In addition to qualitative combined well log analysis, the time-depth relationship of the sonic log and seismic data was quantitatively determined by tying a well with an intersecting seismic section to validate the stratigraphic facies horizons identified. Four well log facies and their environments of deposition were characterised from the combined well log analysis of the different log types. It is discovered that the Cretaceous basement structural features controlled the deposition of overlying formations in the basin. Without intact core data, the shallower wells were discovered to have bottomed over subsurface horst features while deeper wells penetrated into the basal facies contained mainly within the grabens. Main subsurface structural lineaments in the area include NW-SE, NE-SW and NNW-SSE trending faults, which mainly formed the horst and graben features. Some stratigraphic formations described in previous generalised stratigraphic schemes for the Bornu Basin were herein not found in the north-eastern part of the basin.

## 1. Introduction

Bornu Basin is one of the most explored inland basins in Nigeria and its hydrocarbon potentials have been well identified (Petters and Ekweozor, 1982; Avbovbo et al., 1986; Genik, 1992; Genik 1993; Olugbemiro, 1997; Moumouni et al., 2007; Obaje, 2009; Anakwuba and Chinwuko, 2012; Hamza and Hamidu, 2012; Adepelumi et al., 2012). Several discrepancies exist in the literature for the litho-stratigraphic classification of the Bornu Basin. The subsurface stratigraphy in the north-eastern part of the basin towards the south western shores of the Lake Chad remain unclear since specific data were routinely used and not a combination of different datasets, which allow for correlation and validation. The stratigraphy of the Bornu Basin was thus commonly associated with the stratigraphy of its south adjoining Gongola Basin in the Upper Benue Trough. Bornu Basin is an inland sub-basin within the south-western boundary of the Lake Chad Basin and forms part of the regional Cretaceous West and Central African Rift System (WCARS) basins (Binks and Fairhead 1992; Genik, 1992). The Lake Chad Basin is a large intracontinental basin which covers areas in Nigeria, Republic of Chad, Republic of Niger, Libya, Cameroon and Central African Republic. Thus, Bornu Basin is the Nigerian sector of the Lake Chad Basin located in north-eastern Nigeria and characterised with semi-arid climatic conditions typical of the Sudan and the Northern and Central Africa (Miller et al., 1968; Isiorho and Matisoff, 1990; Isiorho, and Nkereuwem, 1996) (Figure 1).

Generally, bedrock outcrops in the basin are scarce, mainly covered by thick Quaternary sediments forming broad flat terrain in the north towards the south-western boundary of Republic of Chad and the Lake Chad (Isiorho, and Nkereuwem, 1996). However, few rock outcrops were found in the southern part of the basin towards its boundary with the Upper Benue Trough (Obaje, 2009; Boboye and Akaegbobi, 2012; Chinwuko et al., 2012; Hamza and Hamidu 2012). The limited outcrops mapped using traditional field methods were used to generalise the stratigraphy of the entire basin. The stratigraphic investigations carried out in localised parts of the basin using the geological field mapping were therefore inadequate since the greater part of the basin in the northern part remained constrained by flat topography and inadequate bedrock outcrops. Previous subsurface stratigraphic studies in the north-eastern part of the basin which involved few core samples or segregated ditch cuttings were obtained from few wells (e.g., Moumouni et al., 2007; Boboye and Abimbola, 2009; Alalade and Tyson, 2012; Hamza and Hamidu, 2012; Boboye and Akaegbobi, 2012; Adeigbe et al., 2013; Adegoke et al., 2014). Similar previous studies including gamma ray log

analysis; Adepelumi et al. (2012) and 2D seismic data analysis; Avbovbo et al. (1986); Okpikoro and Oluronniwo (2010) were insufficient in identifying detail subsurface stratigraphy of the north-eastern part of the basin. Consequently, in the absence of bedrock outcrops and intact core samples, this study presents an alternative effective subsurface stratigraphic study using multi-well log data including gamma ray, resistivity, bulk density and sonic logs obtained from the complete twenty three (23) wells drilled in the basin and intersecting 2D seismic data.

The primary objective of this study is to constrain the subsurface stratigraphy in the north-eastern Bornu Basin bordering the Lake Chad using combined seismic and well log data. Specifically, the study aim at (1) correlating the multiple well log datasets, (2) tying well log data to seismic data for validation of the stratigraphy, (3) detailed seismic facies interpretation, (4) detailed well log facies interpretation, (5) identifying the sedimentary formations and delineating their thicknesses and lateral variations, (6) deducing the environments of deposition of the formations, (7) characterising the subsurface seismic lineaments and (8) identifying the synergy between combined application of the different data types. The main advantage of the integrated data analysis is to provide more detail subsurface analysis which would enhance reliability of geological interpretations than using any single data only.

## **2. Geological and tectonic background**

Bornu Basin is an intra-cratonic basin which evolved from the Cretaceous extensional rifting that followed the separation of the African and South American plates at a Rift-Rift-Fail (RRF) triple junction earlier linked from Niger Delta (Grant, 1971; Olade, 1975; Burke, 1976). Bornu Basin, earlier known as “Maiduguri sub-basin” (Avbovbo et al. 1986) is an east-west elongated inland sub-basin in the south-western boundary of the Lake Chad Basin in north-eastern Nigeria covering Latitude  $11^{\circ}.00'N - 13^{\circ}.45'.38''N$  and Longitude  $8^{\circ}.21'.49''E - 14^{\circ}.40'.22''E$  (Olugbemiro et al., 1997). Bornu Basin referred to as the Nigerian sector of the Lake Chad Basin makes up approximately ten percent of the 230,000 km<sup>2</sup> extent of the entire Lake Chad Basin (Figure 1). The southern flank of the Chad Basin which constitutes the Bornu Basin is bounded by Upper Benue Trough (Alalade and Tyson, 2010) (Figure 1). The study area is in the north-eastern sector of the Bornu Basin covering Latitudes  $12^{\circ}00'N - 13^{\circ}30'N$  and Longitudes  $12^{\circ}30'E - 14^{\circ}00'E$ .

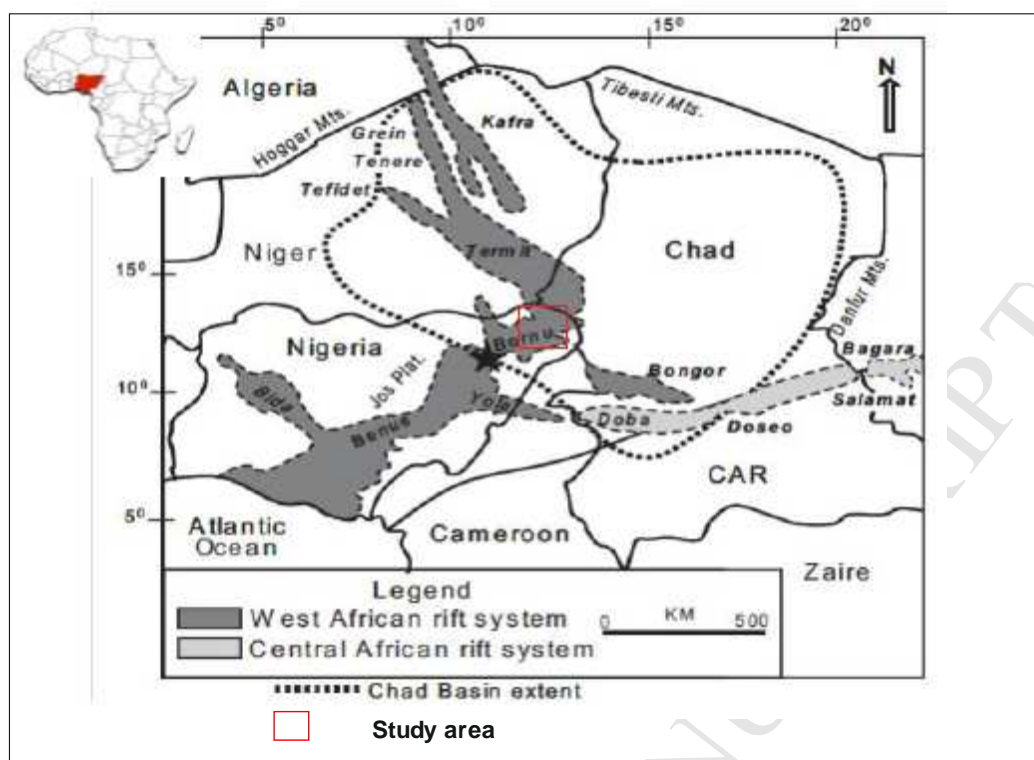
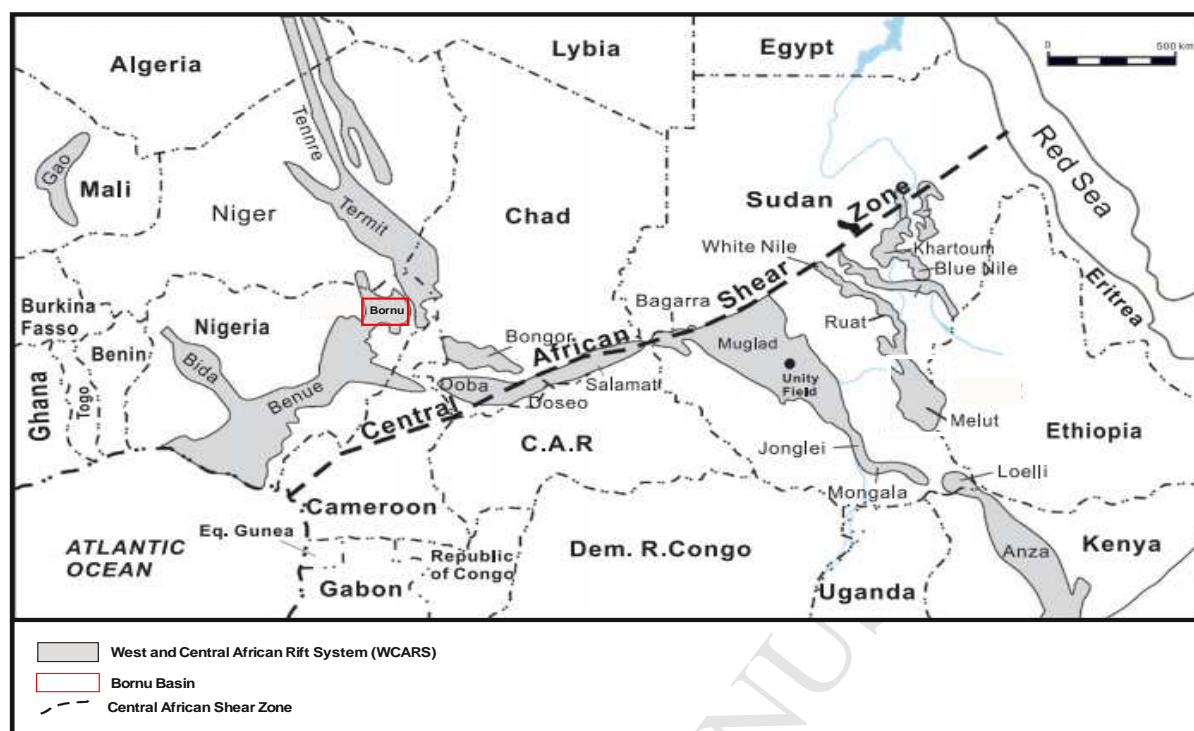


Figure 1. Map showing location and extent of Lake Chad Basin including the north-eastern Bornu Basin in north east Nigeria (modified from Alalade and Tyson 2010).

Bornu Basin is part of a regional active tectonic setting with characteristic structures extending NW to the Air Mountains and SW to the Benue Trough (Ajayi and Ajakaiye, 1981). The Lake Chad Basin and its constituent Bornu Basin were classified as rift basins based on several evidences including presence of basement tensional force indicators, zig-zag fault patterns and lack of compressive features of the main rift event in Early Cretaceous – Tertiary (130 - 96 Ma) (Avbovbo et al., 1986). Late Cretaceous Albian-Cenomanian rift (96 – 75 Ma) resulted into thermo-tectonic subsidence followed by Tethys sourced marine transgression through Mali and Algeria into western Niger with an analogous South Atlantic sourced marine transgression through Nigeria into western Chad and eastern Niger. The peak of marine transgression during the period 85 – 80 Ma was followed by regression as a result of epeirogenic uplift which affected the basin and formed major compression in the Santonian. The Santonian compression resulted into separation of the WCARS into discrete basins (Figure 2) with several associated hydrocarbon trapping features (Genik, 1993) and folds in Benue Trough and Bornu Basin (Popoff et al., 1983; Cratchley et al., 1984; Avbovbo et al., 1986; Benkhelil, 1988).

119



120

121 Figure 2. Regional map of West and Central African Rift System Basins (WCARS) developed from the Cretaceous  
 122 continental separation (modified from L. Dou et al., 2007).

123

124 Evidences from water boreholes and geophysical well logs indicate that the Upper Benue  
 125 Trough was genetically related to the Bornu Basin. The Zambuk ridge granitic inlier  
 126 separates Bornu Basin with the Benue Trough (Figure 3) such that sedimentation in the  
 127 basins were not the same (Avbovbo et al., 1986; Alalade and Tyson, 2010; Adepelumi et al.,  
 128 2010, Okpikoro and Olorunniwo, 2010).

129 Conversely, Zaborski et al., (1997) and Hamza and Hamidu (2012) rebuffed the notion of  
 130 Zambuk ridge separation and indicated that the N-S trending Gongola Basin in the Upper  
 131 Benue Trough was separated with the Bornu Basin by an anticlinal Dumbulwa-Bage High  
 132 (Figure 3). The generally low lying topography of the Bornu Basin is mostly interrupted by  
 133 sand deposit spanning several km in the basin. Geophysical evidence indicated that the Benue  
 134 rift valley was filled with about 5500 m of folded Cretaceous sediments extending north-east  
 135 from the Niger Delta to the Chad Basin. The central axis of the Benue valley is characterised  
 136 by a positive gravity anomaly flanked by negative gravity anomalies on either sides. The  
 137 negative anomalies were suggested to be due to combination of crustal thinning, presence of  
 138 basic intrusives and shallow basement rocks (Cratchley and Jones, 1965).



Rock outcrops in the Bornu Basin are generally scarce as they are mostly covered by Quaternary sediments. The basin is characterised by flat topography and gentle slopes (Isiorho, and Nkereuwem, 1996) and inadequate continuous bedrock outcrops especially in the northern parts towards the boundary with the Republic of Chad and the Lake Chad in the north-east (Figure 4). Most bedrock exposures were confined in the southern boundary with the Gongola Basin (Hamza and Hamidu 2012). Carter et al. (1963) and Avbovbo et al. (1968) presented the generalised stratigraphic scheme for the Bornu Basin (Table 1). The scheme indicated Cenomanian Bima Sandstone as the oldest formation which overlies an unnamed 'Pre Bima' Formation on the basement. Bima Sandstone was a product of weathering of the basement rocks and representing the Continental Intercalaire deposit in Nigeria (Adepelumi et al., 2012). Bima Sandstone was overlain by Gongila Formation deposited from the Turonian transgression and comprised of alternating sand and shale layers with limestone interbeds. Senonian marine Fika Shale overlies the Gongila Formation and marked the end of Cretaceous deposition in the basin. Subsequent regression deposited Gombe Sandstone which was overlain by Tertiary Kerri-Kerri Formation made up of iron rich sandstone and clay with lateritic cover. Quaternary Chad Formation is the topmost layer consisting of alternating sequence of clay with sand interbeds.

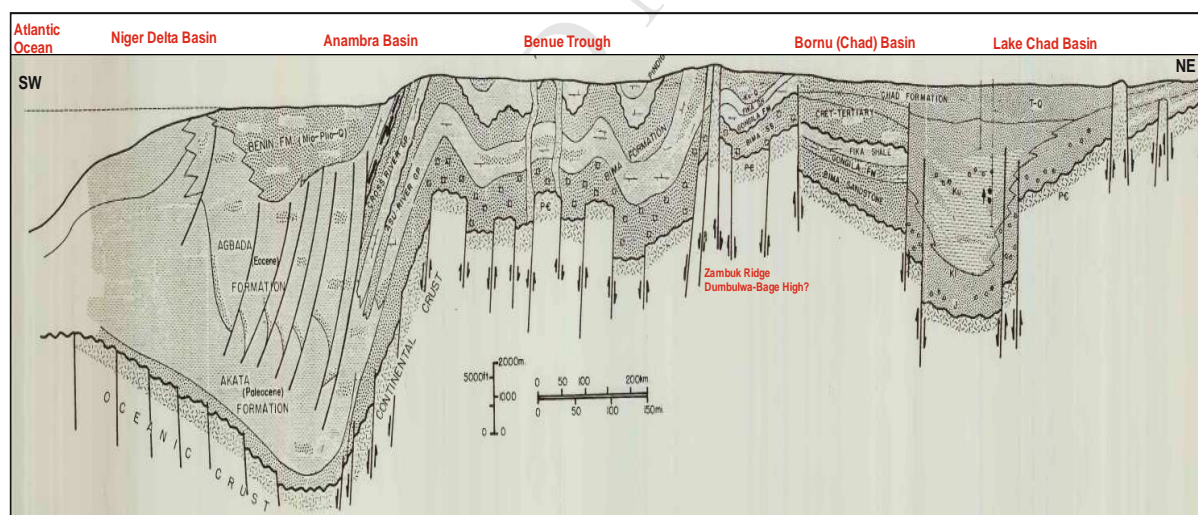


Figure 3. Sketch of tectonic and depositional setting of Bornu Basin and adjoining basins (Modified from Peterson, 1985).

The stratigraphic scheme by Carter et al. (1963) consisting of seven stratigraphic units was confirmed by Avbovbo et al. (1986) while Umar (1999) and Okpikoro and Olorunniwo, (2010) mapped six stratigraphic units using 2D seismic data. Adepelumi et al. (2012) indicated the presence of the six subsurface stratigraphic units including Gombe Formation and Kerri-Kerri Formation using gamma ray log data analysis. However, (Isiorho and

Nkereuwem, 1996) indicated that Chad Formation is completely buried at the north-eastern area by an overlying “post Chad Formation” consisting of aeolian, fluvial and lacustrine sediments with thickness of 1 to 6 m (Figure 5).

Table 1. Generalised stratigraphy of the Bornu Basin (modified from Avbovbo et al 1986).

Period/Epoch	Formation	Average thickness (m)	Thickness from seismic data (m)	Lithology
Quaternary	CHAD	400	800	Clays with sand interbeds
Tertiary	KERRI-KERRI	150		Sandstone and clay with laterite
Maastrichtian	GOMBE	315	0-1000	Sandstone, siltstone and clay with coal beds.
Senonian	FIKA	430	0-900	Shale, with limestone beds
Turonian	GONGILA	420	0-800	Alternating sandstone and shale with limestone
Cenomanian	BIMA	3050	2000	Sandstone
Albian	UNNAMED	-	3600	-
	UNNAMED	-	0-3000	-
Precambrian	BASEMENT			-

Late Tertiary volcanism was common in the southern and central parts of the basin (Grant, 1971). Peters (1978) and Okosun (1995a) however, indicated that five stratigraphic units including Bima, Gongila, Fika, Gombe, Kerri-Kerri and Chad Formations were deposited in the basin. Burke, (1976) used water borehole data and established that deposits of Kerri-Kerri Formation in the basin were localised, forming a thickness of 300 m from the Jos Uplift and terminated in the Maiduguri area. Kerri-Kerri Formation was exposed only in the western parts of the basin beneath the Chad Formation and absent in the south western parts (Miller et al., 1968).



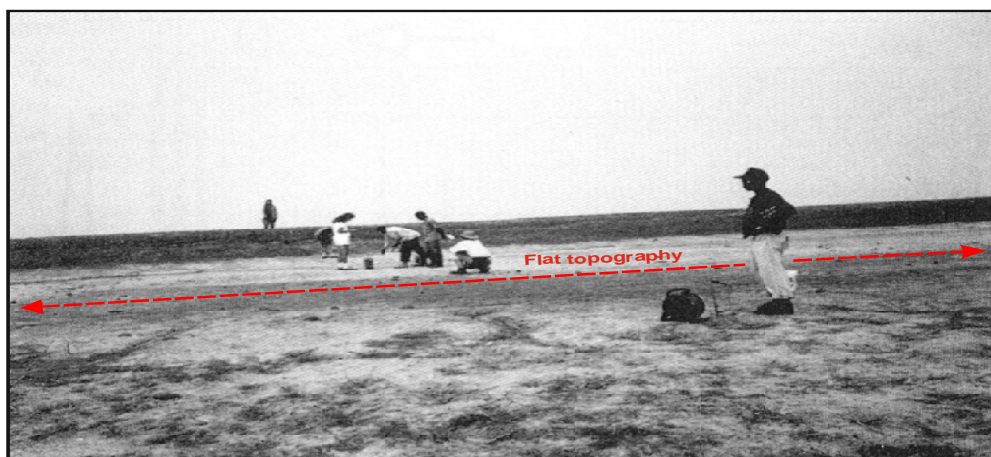


Figure 4. Image showing typical flat terrain and lack of outcrops in the north eastern Bornu Basin (Modified after Isiorho and Nkereuwem, 1996).

Four subsurface stratigraphic units including Bima, Gongila, Fika and Chad Formations were discovered in few core samples with no evidence of Gombe Formation and Kerri-Kerri Formation underlying the north-eastern Bornu Basin (Olugbemiro et al., 1997; Moumouni et al., 2007; Boboye and Abimbola, 2009); Alalade and Tyson, 2010).



Figure 5. Image showing thick Post Chad deposit overlying the Chad Formation (Modified after Isiorho and Nkereuwem, 1996)

However, the facies lateral distributions across the north eastern area have not been presented so far. Hamza and Hamidu, (2012) produced a different generalised stratigraphic scheme for the basin and added new Formations using segregated ditch cutting samples from four wells in the north-eastern area combined with outcrop mapping in the southern boundary of the basin (Table 2). The stratigraphic classification by Hamza and Hamidu, (2012) renamed the Bima Formation as Bima Group subdivided into Lower, Middle and Upper units while the overlying Gongila Formation was subdivided into Formation 1 and Formation 2. Fika Shale

which overlies the Gongila Formation was subdivided into three including Formation 3, Formation 4 and Formation 5 (Table 2).

Table 2. Generalised stratigraphic scheme for Bornu Basin (Modified after Hamza and Hamidu 2012).

Formation		Period/Epoch
Chad Formation		PLEISTOCENE - PLEISTOCENE
Kerri-Kerri Formation		PALAEOCENE-EOCENE
Gombe Sandstones		MAASTRICHTIAN
FIKA SHALE	'FORMATION 5'	CAMPANIAN
	'FORMATION 4'	SANTONIAN
	'FORMATION 3'	CONIACIAN
'FORMATION 2'		UPPER
		MIDDLE
		LOWER
		TURONIAN
'FORMATION 1'		CENOMANIAN
BIMA GROUP	'Upper Bima Formation'	ALBIAN
	'Middle Bima Formation'	APTIAN
	'Lower Bima Formation'	Pre-APTIAN
++ Crystalline basement ++		PRECAMBRIAN

Gombe Formation and Kerri – Kerri Formation were indicated beneath the uppermost Chad Formation. So far, none of these previous stratigraphic studies in the north-eastern area of the Bornu Basin were validated using combined multiple geophysical data correlation.

### 3. Materials and methods

Exploration in the Bornu Basin by a consortium of oil companies including Halliburton, Landmark and LMK Resources in 1976 led to the drilling of twenty three (23) exploration wells. In this study the complete suite of available well log data from the 23 wells comprising of gamma ray (GR) log, resistivity (ILD) log, bulk density (RHOB) log and sonic (DT) log in each well and analysed for detailed mapping of subsurface stratigraphy and structures. Additional data include post stack time migrated 2D seismic reflection survey data located at the wells positions in the north-eastern Bornu Basin adjoining the Lake Chad. The data were provided by the Nigerian Department of Petroleum Resources (DPR) and Nigerian National Petroleum Corporation (NNPC). Sonic log velocity data were extracted from Kasade\_01 (KAS) well, which is directly located on the NE-SW oriented seismic Line\_13 was selected for the well-to-seismic tie using their time-depth relationship. NW-SE oriented seismic Line\_5, which perpendicularly intersects seismic Line\_13 was selected for correlation and validation of the seismic stratigraphy (Figure 6).

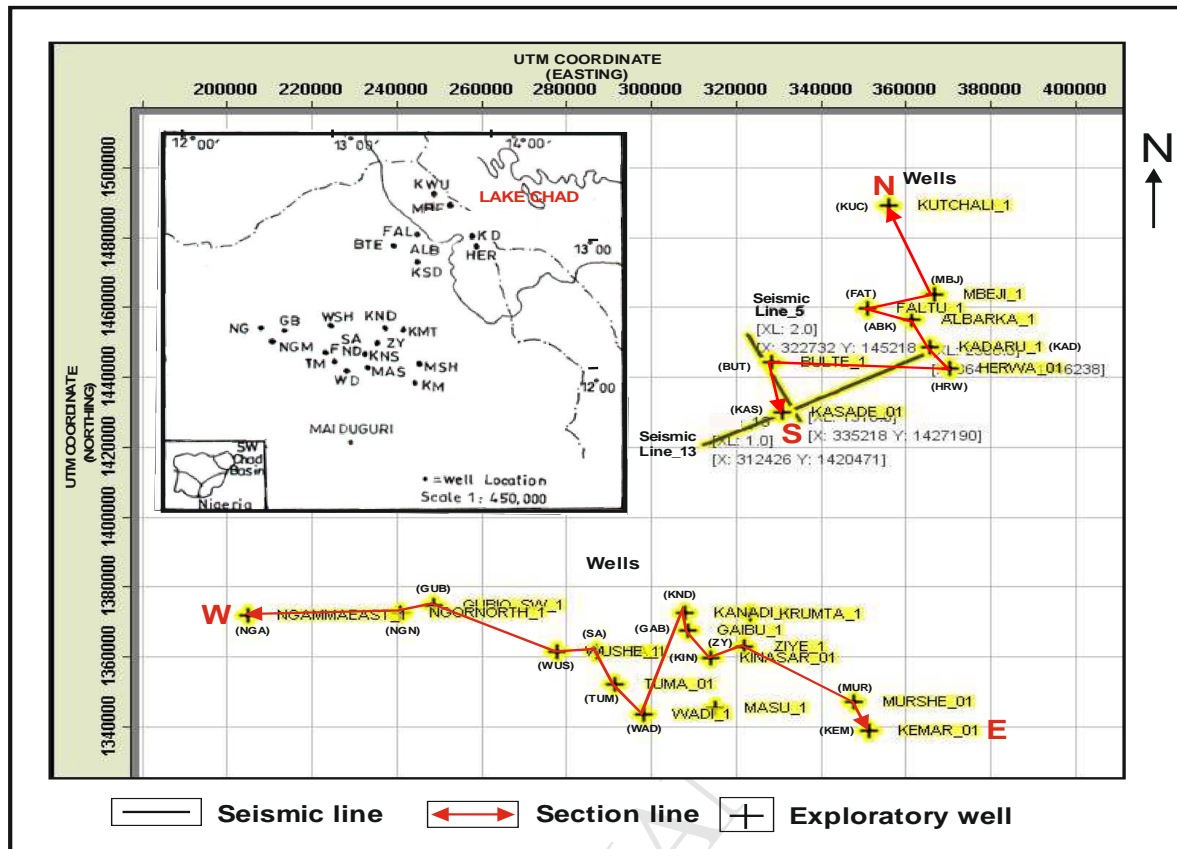


Figure 6. Distribution of seismic and well log data used for this study. (Insert is map of north eastern Bornu Basin showing data coverage in the north-eastern Bornu Basin north east Nigeria modified after Hamza and Hamidu, 2012).

The 2D seismic data were displayed in normal SEG-Y polarity with downward increase in reflection time for a zero phase wavelet reflection wiggle and a positive reflection coefficient having a central wavelength peak. The processed seismic sections possessed high signal-noise (S/N) ratio with smooth and continuous phase reflections, which allow for easy auto tracking of the strong seismic reflections and more reliable manual horizon mapping where necessary. In the absence of rock outcrop and core samples for this study, the universal lithological descriptions of the formations in the basin from published studies were used as guide for identification of the stratigraphic facies units described herein.

Four different log types including gamma ray, resistivity, bulk density and sonic logs were analysed to establish their synergistic relationships with depth in the wells. The method involved delineating the different geophysical responses of the different log types and their corresponding log curve pattern behaviours in different lithological environments penetrated by each well. Patterns are correlated across different logs at depth in each well and compared across corresponding logs in all wells.

Generally, well logs are generated from geophysical instruments lowered down in well bores to record changes in subsurface physical properties of rocks with depth. The data obtained have several applications in the different fields of geology but they are particularly useful in the oil and gas industry for evaluation of hydrocarbon fluids as well as in stratigraphy and structural geology (Asquith and Gibson, 1982). Subsurface stratigraphic correlation generally relies on the analysis of well log data to build cross sections, subsurface maps and geological models using common correlation methods including use of marker beds, pattern matching and slice techniques (Modibboyina and Rao, 2011). Log pattern matching can be carried out manually (Schaefer, 2005) or using mathematical, logical, or other advanced computing techniques to recognise patterns in well logs for classification into electrofacies (Igbokwe, 2011). The physical relationship between most geophysical methods including well logging and seismic survey are commonly compared for precise interpretation of subsurface stratigraphy and structures and to improve understanding of subsurface heterogeneities (Bueno et al., 2014). Stratigraphic units in this study were identified from qualitative pattern analysis of the different logs and validated using seismic data. The methodology involved correlating the time-processed seismic data to the depth-processed sonic log velocity data to determine their time-depth relationship.

Stratigraphic horizons were mapped from reflection surfaces in the 2D seismic data to represent subsurface lithological interface or sequence stratigraphic boundaries. As well velocity or check-shot survey data is not available for direct time-depth tying of the seismic to well data the correlation method described by Herron (2014) was tested herein using time-depth components available in the sonic log data. Routine smoothing and coarsening of the plotted well logs' scales to fit the data range were applied. Vertical axes or the measured depth (MD) axes of the well logs were adjusted to conform with data-start to data-stop ranges for whole log visualisations. Consistency in log signatures with depth across different log types in each well were observed by visually recognising and mapping patterns of the logs. Each visual log pattern is associated with a corresponding qualitative indication of the physical property measured by the log. Fine correlations within likely formations as well as at formation boundaries across well sections rather than absolute conformity of the log patterns were considered. Mapping of stratigraphic intervals were achieved by analysing overall log patterns and their corresponding change in log values that is consistent with the expected log behaviour associated with individual lithologies. Pattern analysis and recognition of log behaviours in different rocks were derived from the synthetic log response chart developed by Railsback (2011). Log profiles were plotted and correlated across the wells along two

section lines N-S and E-W (Figure 6) to map the lateral continuous subsurface stratigraphy and structure (Figure 7 a,b).

## 4. Results

### 4.1 Stratigraphy and basin structure

Qualitative analysis of the well logs resulted in characterisation of the subsurface stratigraphy into well log facies. The gamma-ray (GR), resistivity, bulk-density and sonic logs from all wells were arranged into vertical profiles against common measured depths to show systematic vertical variations of the sedimentary sequence across different log types at corresponding depths in each well. Abrupt changes observed in the overall log patterns with associated change in individual log values were implied as change in the lithology or stratigraphic boundary. Typical log responses associated with the various lithologies described by Railsback (2011) were used for the qualitative interpretation of subsurface facies units. Descriptions of the main lithologies in Bornu Basin indicated that the formations predominantly contained varying proportions of sand and shale or clay (Table 1). As such, qualitative analysis based on the dominance of shale or sand as indicated by their corresponding log responses at any depth within the formation were inferred. Results were obtained by outlining the intervals within the logs which display certain characteristic curve shape and deducing the magnitude of the log response within corresponding stratigraphic depth as described by Kassenaar (1989). Four well log facies were identified and correlated with their corresponding seismic facies identified from interpreted seismic sections in (Figures 11 & 12) to validate the stratigraphy and structure.

#### 4.1.1 Gamma ray log

Gamma ray log used herein were analysed mainly to distinguish shale and non-shales (or sandy) compositions. Conventionally, gamma ray (GR) log is primarily used to detect the presence of radioactive materials that make up clay particles in shales. As such, gamma ray (GR) log is commonly referred to as the 'shale log' (Kenneth and Allan, 2003; Ellis and Singer 2007). The GR log were displayed in two narrow columns for measured depths (MD) and the log track recorded in standard American Petroleum Institute (API) units. The scale of 1 – 150 API was used to accommodate the general response range of the gamma ray log data.



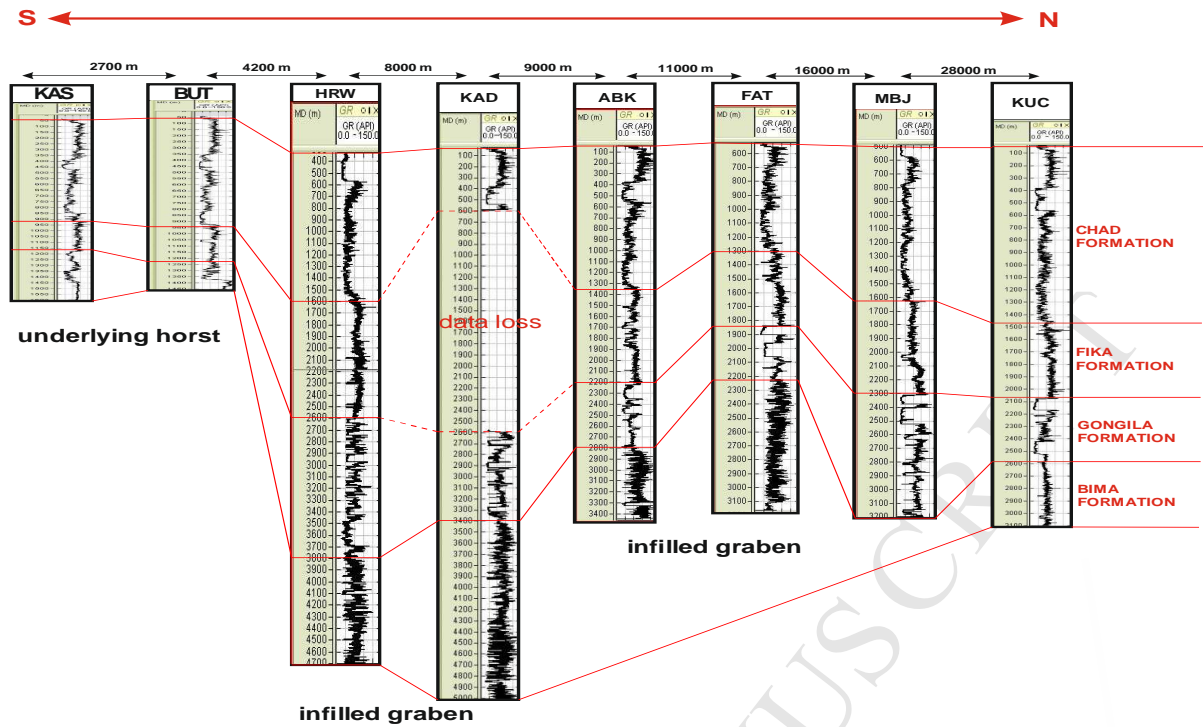


Figure 7 (a) N-S oriented cross section of wells as shown in Figure 6, showing interpreted subsurface stratigraphic correlation and basin structure

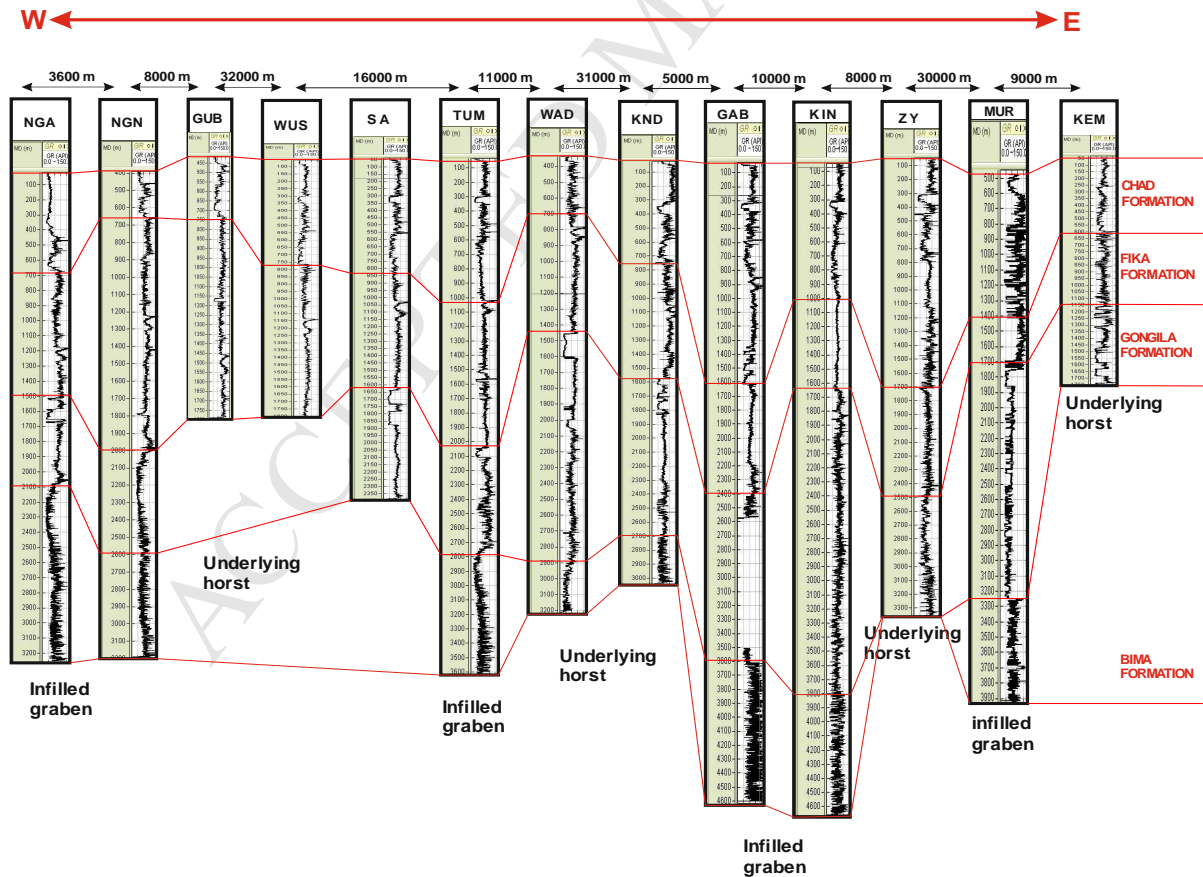


Figure 7 (b) E-W oriented cross section of wells as shown in Figure 6, showing stratigraphic correlation and basin structure.



Sudden changes in GR log curves pattern inferred changes in lithological property or unconformities producing systematic curve trends (Krassay, 1998). However, this does not conclusively imply that all increased gamma ray responses in GR log signify shale content since sand layers may contain radioactive materials (Ellis and Singer, 2007). Gamma ray responses can more reliably be attributed to grain sizes when correlated with outcrop or core samples. Krassay, (1998) classified three commonly recognised gamma ray log shapes, which infer discrete sedimentary cycles. Funnel-shaped gamma ray log with gamma ray counts decreasing upward indicating progressively coarser or sandy sedimentary sequence denote progradational stacking pattern. Bell-shaped gamma ray log with gamma ray count increasing upward indicating finer or shaly sedimentary sequences denote retrogradational stacking pattern. Block-shaped gamma ray log with regular gamma ray counts indicating uniform sedimentary sequence denote aggradational stacking pattern. These characteristic log shapes are more apparent when the GR log is paired with resistivity log where the patterns are mirrored (Figure 8).

Well-log interpretation herein using the CLP method utilised mirrored gamma ray and resistivity logs with bulk density and sonic logs compared in each well to delineate the general behaviour of the curves corresponding to overall grain size and mineralogy for correlation. Four well log facies units WF1, WF2, WF3 and WF4 were identified in all wells from combined well log interpretation as illustrated with Faltu\_1 well (Figure 8). The basal well log facies unit 1 (WF1) were associated with closely spaced log curves, less spiky with predominantly low GR log values and regular or blocky overall trend typical of a predominantly sandy unit. The overlying WF2 exhibit very spiky and spread-out log curves associated with alternating sharp increase and decrease in GR log values which generally decreased upward forming an overall funnel shape typical of alternating sand and shale sequence. WF3 is characterised with very closely spaced GR log curves associated with high GR values with none or occasional spikes and an overall blocky curve trend typical of a dominantly shale unit. The uppermost WF4 is characterised with less closely spaced curves, often spiky and alternating sharp changes in log curves with associated variable log values which generally increased upward formed overall bell shape curves. WF4 is typical of alternating sand and clay sequence. Log data from two wells namely Masu\_01 and Krumta\_01 (Figures 6 and 7b) were not plotted due to high data breaks. Geological interpretations are based on the remaining 21 wells.

#### 4.1.2 Resistivity log

Resistivity logs measure electrical properties of rock formations and are usually correlated with gamma ray logs for lithological investigation due to their distinguishing behaviours in sand and shale formations. Quartz and muscovite, which are abundant mineral components in sandstones have high resistivities while clays in shales have low resistivities. However, resistivity of formations often depends on conductivity due to the presence of water (and its salinity) and hydrocarbons contained within pores spaces of rocks. Resistivity depends on the lithology due to the nature of rock fabric, texture and clay content (Ellis and Singer, 2007). In this study, the resistivity log type is the deep induction log (ILD) which measures resistivity around the wellbore in the undisturbed deeper zones of the formation uninvaded by the drilling mud fluid. The log scale was set at a range of 0.2 – 100 Ohms which fitted the extent of the data. The log tracks have logarithmic grid line scales to accommodate the changes associated with electrical measurements in rocks. The ILD logs are essentially used herein to distinguish between zones of shale and non shaly (or sand) across the formations. Thus, inverse pattern behaviour was expected between the GR logs and the ILD logs where minimum resistivity readings would indicate high clay and shale content and maximum resistivity readings would indicate the sandy content (in the absence of oil and or associated formation water). The resistivity log responses generally display a consistent contrasting pattern behaviour compared with the GR logs at every defined depth interval in each well (Figure 8). This contrasting pattern behaviour between the GR and ILD log pairs was used to mirror the combined overall log pattern to detect bell, blocky and funnel shapes.

#### 4.1.3 Bulk-Density log

Bulk density is an important property of rock formations as it directly relates to in-situ porosity, lithology and pore fluids. Unlike the natural GR log which measures the in-situ radioactive materials in rocks, bulk density measurements in wireline logging use active gamma ray source with gamma ray detector device to record Compton scattering interactions (Ellis & Singer, 2007). The bulk density log (RHOB) has a unit scale set at 1.45 – 2.65 g/cm<sup>3</sup> according to the range of the data. Changes in RHOB log pattern the result of variation in density of the rock formations due to porosity difference between sandstones and shales is the major distinguishing property used herein for identification of the lithology. Sandy zones display higher bulk density values than the shale zones with even higher values with depth of burial in the sandstone zones (Figure 8).

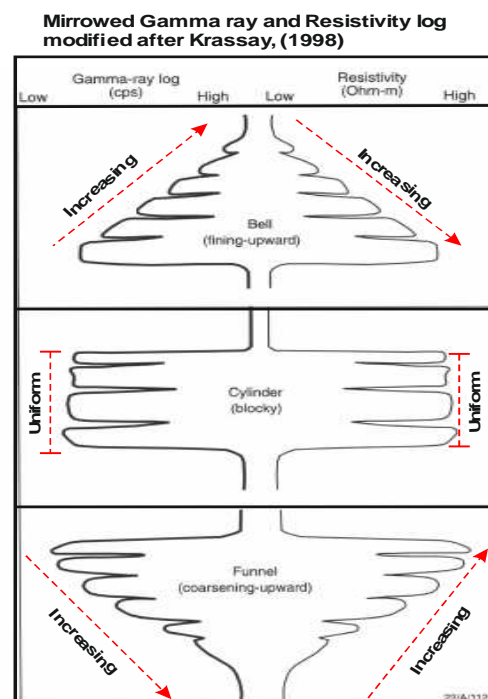
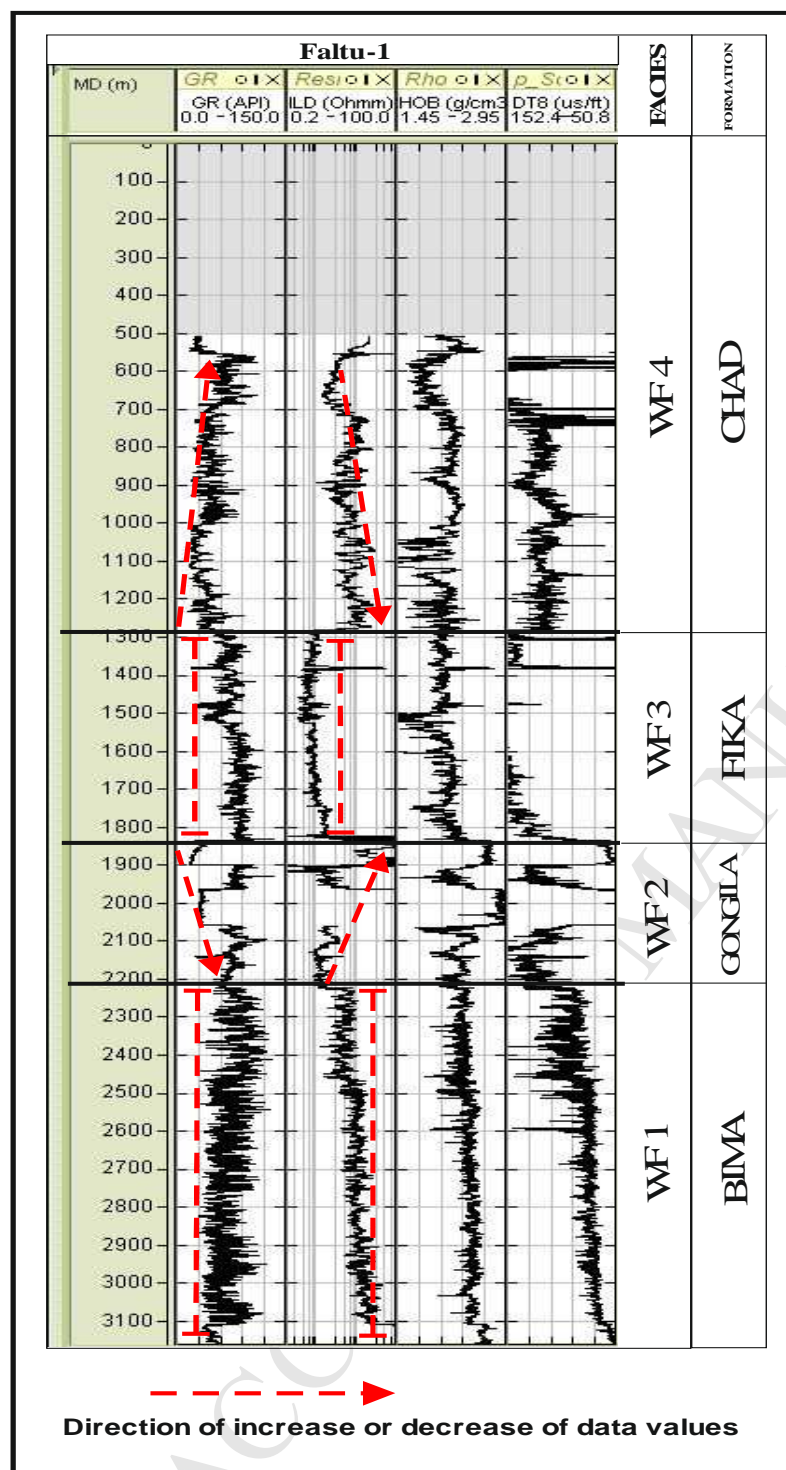


Figure 8 (a). Faltu\_1 well log showing an example of the CLP stratigraphic facies analysis. (b) Illustration of the mirrored well log curves.

#### 4.1.4 *Sonic log*

Sonic logs measures the acoustic velocity of the compressional (P) or shear (S) waves travelled in rocks which primarily depends on the density, porosity, and lithology of the rock medium. However, the P waves depends more on the bulk density of the propagating medium. Sonic logs measure the transit time or slowness of the waves in the formations around the well bore such that the wave travel time is lower in high porosity rocks including sandstone and higher in low porosity rocks including shale. The inverse relationship between bulk density and P-wave velocity is qualitatively reflected in their log patterns (Gardner et al., 1974). The sonic log type available in the dataset is the P-sonic with unit scale ranging from 50.8 – 152.4  $\mu\text{s}/\text{ft}$  to fit the extent of the data. The sandy zones in this study clearly displayed high density and a corresponding low p-sonic value while other zones with comparative low density values and corresponding high sonic values are the shale zones (Figure 8).

#### 4.2 *Well log facies interpretation*

The four well log facies WFI, WF2, WF3 and WF4 representing Bima, Gongila, Fika and Chad Formations respectively were identified from the combined well log analysis of the four different log curve characters with depth in the 21 wells (Figure 8). Delineation of corresponding boundary intervals across the different types of well logs for each well allows for the stratigraphic subdivision of the well log facies into different genetic groups with lateral relationships. The lithofacies displayed consistent distinct pattern behaviour in the GR and resistivity log pairs and correlated with the bulk-density and sonic logs corresponding to individual sedimentary cycles. Each lithofacies is separated from the other by an observable sudden change in log pattern with associated changes in the multi-log physical properties and log values due to the distinctive change in lithology. In this study, due to the absence of core log samples, which would have contained detailed petrographic and biogenic components in the subsurface rocks, the well log facies analysis relied on the generic lithostratigraphic descriptions of the formations in Bornu Basin by Avbovbo et al. (1986) (Table 1) to deduce and assign the corresponding lithostratigraphic unit. Lithofacies identified were designated into strata and characterised into stratigraphic intervals to interpret the various depositional and stratigraphic framework for the study area from the basal to the upper units. Individual facies characteristics are classified based on their differences in lithological composition, thickness, clay content and stratigraphic position.

#### 4.2.1 Well Log Facies 1 (WF1): Bima Formation

WF1 is the basal facies which displayed characteristic blocky-shaped GR and resistivity curves pair largely having both GR and resistivity values vertically unchanging indicating uniform lithology and lack of overall facies change. This general trend is also observed in the corresponding bulk density and sonic logs. GR API values are generally low, resistivity values are generally high, bulk density values are high and p-sonic velocity values are low indicating sandy unit as the basal rock formation (Figure 8). Cross section analysis of the N-S and E-W axes indicate WF1 as the oldest sedimentary unit in the study area with overall thickness ranging from 300 m in Wadi\_1 (WAD) well (Figure 7b) to 1600 m in Kadaru\_1 (KAD) well (Figure 7a). The maximum depth of the WF1 recorded in the study area is 5000 m from (KAD) Kadaru\_1 well which represent the deepest level drilled in the Bornu Basin. Characteristics of WF1 are consistent with the literature description of the basal facies in the basin is herein interpreted as the basal Bima Formation which is the oldest formation in the Bornu Basin deposited over the basement rocks. Bima Formation basically consist of sandstone with even degree of grain size and sediment sorting indicative of a continental depositional environment. The uniform lithology and constant overall facies character indicate an aggradational sedimentary stacking pattern.

#### 4.2.2 Well Log Facies 2 (WF2): Gongila Formation

WF2 unit directly overlies the WF1 and it displayed characteristic overall funnel-shape in combined GR and resistivity curves pair often with repeated alternating block intervals of GR and resistivity spikes. Similar distinguishing trend was observed in the bulk density and sonic logs indicating alternating shale- sandstone facies sequence. Cross section analysis of the N-S and E-W axes (Figure 6) in the area indicated that this layer overlies the Bima Formation with thickness ranging from 200 m in Bulte\_1 (BUT) well (Figure 7a) to 1621 m in Kinasar\_1 (KIN) well (Figure 7b). Characteristics of WF2 are consistent with the literature description of the overlying formation is interpreted as the Gongila Formation. WF2 curves pattern indicate progressive coarsening upward succession representing progradational regressive sedimentation in transitional lacustrine to shallow marine depositional environment.

#### 4.2.3 Well Log Facies 3 (WF3): Fika Formation

WF3 directly overlies the Gongila Formation and displayed characteristic curve pattern similar to WF1 except for higher GR values with corresponding lower resistivity values, lower density values and higher p-sonic velocity values indicative of uniform shale layer (Figure 8). Cross section analysis of the N-S and E-W axes indicate that the WF3 layer ranges in thickness from 255 m in Kasade\_1 (KAS) well to 1349 m in Ngornorth\_1 (NGN) well (Figure 8). Characteristics of WF3 are consistent with the literature description of the overlying formation represents the mudrock facies unit interpreted as the Fika Shale which consists of predominantly shale. The characteristic blocky shape indicates aggradational sedimentary stacking pattern probably in a transitional lacustrine to shallow marine depositional environment.

#### 4.2.4 Well Log Facies 4 (WF4): Chad Formation

The WF4 unit is the uppermost facies overlying the WF3 displaying characteristic overall bell-shaped GR and resistivity curves pair having GR values increasing upward and resistivity values decreasing upward. Similar pattern were repeated in the corresponding bulk density log and sonic log indicating sequence of sand and clay interbeds (Figure 8). WF4 is interpreted as the Chad Formation which is consistent with the literature description of the topmost formation. Cross section analysis of the N-S and E-W axes indicate the Pleistocene-Pliocene Chad Formation ranges in thickness from 658 m in Ngornorth\_1 (NGN) well to 1711 m in Ziye\_1 (ZY) well representing the thickest formation in the basin (Figure 7b). The combined well log curve pattern indicates a retrogradational and landward movement of shorelines and an overall fining upward succession typical of fluvial and lacustrine depositional environments. The summary of the local stratigraphy of the north eastern Bornu Basin is presented in (Table 3).



487 Table 3. Litho-stratigraphy of the north-eastern Bornu Basin

Period	Formation	Maximum thickness from well log data (m)	Maximum Depth from well log data (m)	Well log facies lithology	Sediment stacking pattern	Environment of deposition
Quaternary	Chad	1711	1711	Mixed sandy and clayey (shaly) sequence	Retrogradational	Fluvial/Lacustrine
Senonian	Fika	1349	3180	Shaly	Aggradational	Lacustrine – Shallow Marine
Turonian	Gongila	1621	3800	Alternating shaly and sandy sequence	Progradational	Lacustrine – Shallow Marine
Cenomanian	Bima	1600	5000	Sandy	Aggradational	Continental

488

489 *4.3 Sonic log - seismic data correlation*

490

491 Tying well log to seismic is generally more precise by correlating wiggle traces  
492 obtained from well-based reflectivity in vertical seismic profile (VSP) or a synthetic  
493 seismogram with reflectivity obtained from the surface seismic data (Herron, 2014). In this  
494 study, a VSP was not acquired nor processed and a synthetic seismogram for the well log  
495 data is not available to match the character of individual well-based reflections with  
496 reflections from the 2D seismic data. However, Kasade\_01 (KAS) well and seismic Line\_13  
497 directly positioned on the same field location are suitable for well-to-seismic tie. Plotting of  
498 the Kasade\_01 (KAS) well and the Line \_13 seismic data was achieved automatically by the  
499 software used from the geographic coordinates inherent in the two datasets (Figure 6). The  
500 2D seismic Line\_13 is a time-processed data in microseconds ( $\mu$ s) and is not converted to  
501 depth scale while the well log data from Kasade\_1 (KAS) well is depth (MD) processed in  
502 metres. Well velocity or check shot survey data were not available and the only source of  
503 velocity data in the well log dataset was obtained from the compressional P-wave velocity  
504 sonic log which is a time-depth data. The time-depth relationship between the sonic log and  
505 seismic datasets were deduced by calculating the two-way-time (TWT) velocity of the sonic  
506 log and compared with the seismic data TWT velocity as described by Herron (2011, 2014).  
507 The concept involves “blocking” that referred to visual averaging of the sonic log by  
508 delineating discrete log intervals based on distinctive boundaries that mark significant  
509 departures from general log patterns and properties. The discrete intervals measured from  
510 Kasade\_01 (KAS) well sonic log have approximately constant interval transit time (ITT)

corresponding to the constant interval velocity of the log (Figure 9). On the sonic log, the distinct step changes in the overall log patterns were marked and intervals characterised with approximately constant log values were noted. Five major boundary intervals were blocked and labelled A through E having corresponding boundaries 1 through 6 with depth on the sonic log. The ITTs at the top of each boundary interval were measured directly from the sonic log with an average uncertainty of  $\pm 6 \mu\text{s}/\text{ft}$  and were used to calculate the TWT in (ms) for each blocked interval using Equation (1).

$$TWT (ms) = \frac{[2 \times ITT (\frac{\mu s}{ft}) \times \text{sonic log interval thickness (ft)}]}{1000 (\mu s/ms)} \quad (1) \text{ (Herron, 2014)}$$

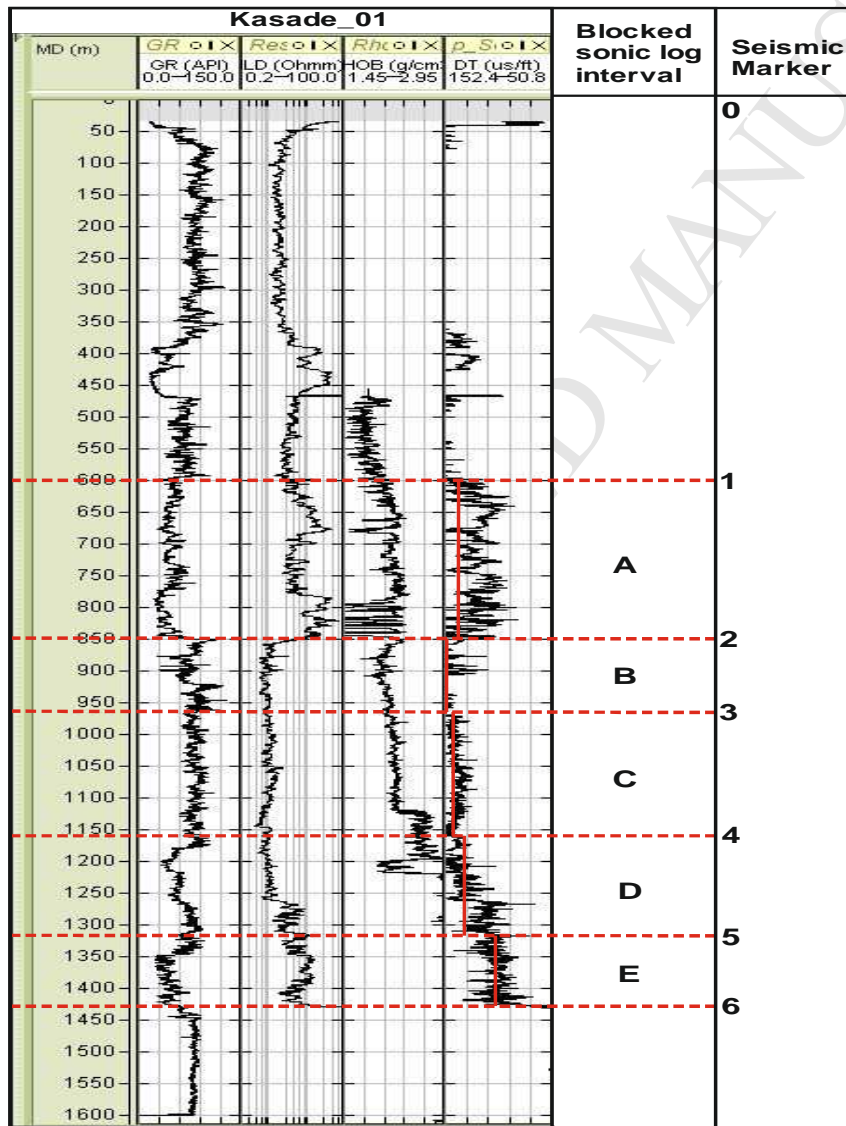


Figure 9. Kasade\_01 well with blocked log intervals and ITT values for sonic log in red (ITT values listed in table 4).

The TWTs calculated for the sonic log blocked intervals A through E in milliseconds became directly comparable with the seismic data having similar unit. Grey scale colour was selected for the seismic data analysis and contrast adjustment was performed to enhance reflection pattern recognition of the seismic section. Distinctive patterns of prominent seismic reflections on the seismic section with stronger amplitude and reflection continuity around the well location were delineated. On the seismic section Line\_13 (Figure 10) six reflection markers 1 through 6 were marked with increasing reflection time. Table (4) shows calculated TWTs of the blocked interval boundaries on the depth-processed sonic log, which correlate with the measured TWTs between corresponding seismic reflection markers on the time-processed seismic data shown in (Table 5).

For example, the calculated TWT for interval A on the sonic log which closely compared with the TWT at reflection marker 1 on the seismic data represented a possible unconformity within the Chad Formation as the top of the formation was not clearly displayed on the sonic log. Close correlation exists between the 272 ms calculated TWT at the sonic boundary interval A with the measured 275 ms TWT between reflections 1 and 2 on the seismic section. Moreover, the calculated 112 ms TWT at interval boundary B closely agrees with the 110 ms TWTs measured between seismic markers 2 to 3 and correlate with the base of the uppermost Chad Formation (Figure 10). The calculated TWT for all the blocked interval boundaries on the sonic log correlate with the measured TWT between their corresponding seismic reflection markers.

Table 4. Blocked Kasade\_01 (KAS) well sonic log data analysis

Interval Boundary	Sonic log Depth (m)	Interval Thickness (m)	Measured Sonic velocity Interval Transit Time (ITT) ( $\mu\text{s}/\text{ft}$ )	Calculated correlated sonic velocity at interval boundary Two-Way-Time (TWT) (ms)
A	600	256	162	272
B	856	119	144	112
C	975	181	151	179
D	1156	119	122	95
E	1275	150	136	134
Base E	1425	-	-	-

Table 5. Time, depth and interval velocity data analysis of Line\_13 seismic

Seismic reflection marker	Direct observed seismic velocity Two-Way-Time (TWT) (ms)	Seismic reflection markers interval and correlated sonic interval boundary	Interval velocity at seismic reflection marker boundary Two-Way-Time (TWT) (ms)
1	544	0 - 1	544
2	819	1 - 2 (A)	275
3	929	2 - 3 (B)	110
4	1105	3 - 4 (C)	176
5	1198	4 - 5 (D)	93
6	1338	5 - 6 (E)	140

The correlation of corresponding TWTs provides the potential for mapping the stratigraphic horizons around the vicinity of the well on the seismic line and thus validating the boundaries of stratigraphic facies identified from the CLP method in (Figure 8).

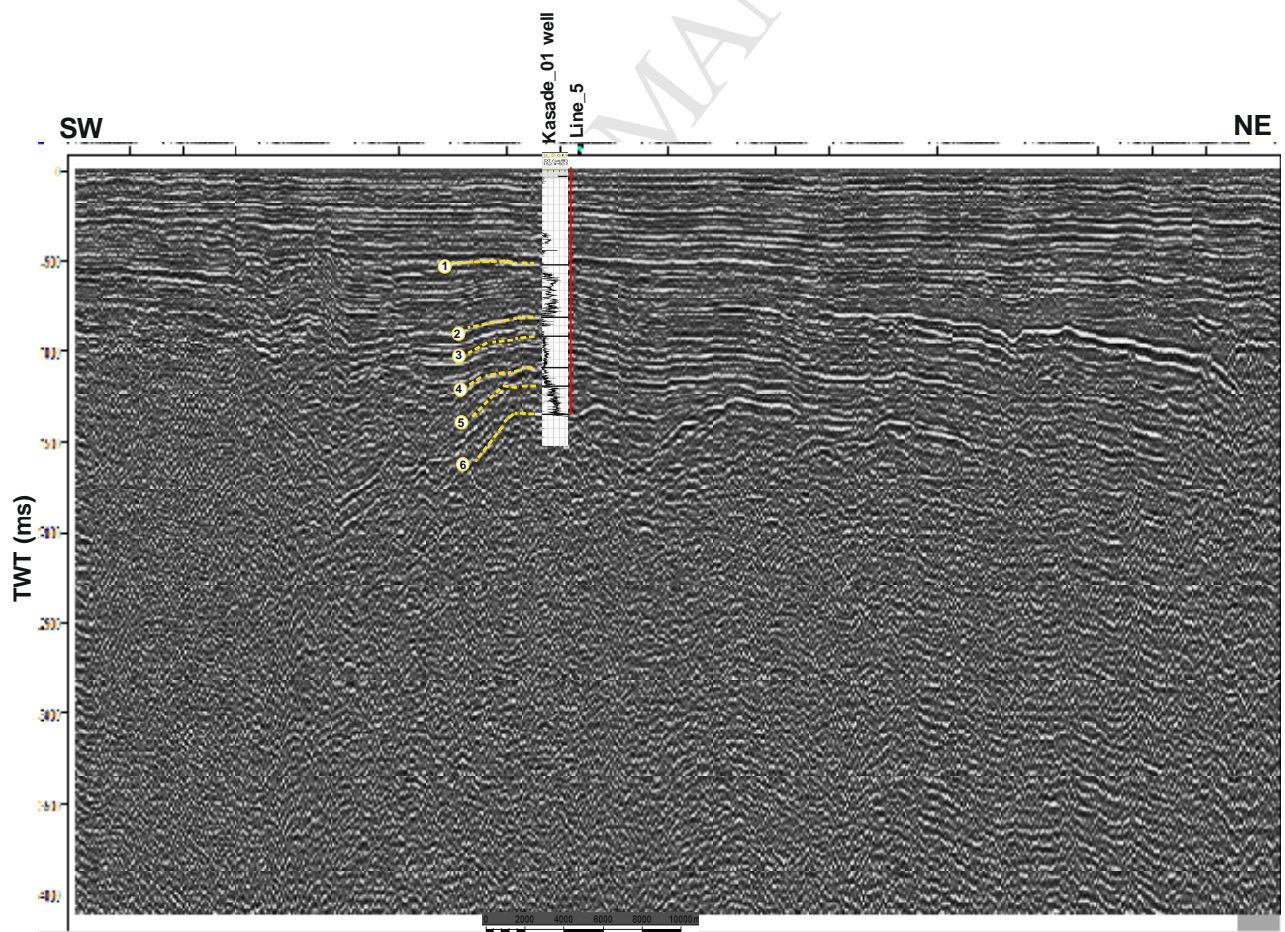


Figure 10. Final correlation of blocked sonic log intervals A – E for Kasade\_01 (KAS) well to reflections 1 - 6 on the intersecting seismic line\_13 (grey scale) shown on Figure 6.



The correlation further illustrates the potential for extending the continuous stratigraphic horizons across adjoining interconnected seismic lines, which do not directly intersect other well positions in the area. (Figure 11) shows the stratigraphy of the area interpreted from the intersecting seismic Line\_13.

#### 4.4 Seismic interpretation

High coherence of reflectors exist in the seismic data, which allowed smooth auto tracking of horizons except where the horizons of interest was tracked along specific weak amplitude peaks or troughs in the seismic section. Correlation of the sonic log interval boundaries with their corresponding seismic reflection markers allowed for the identification of stratigraphic horizons separating the formations delineated. The seismic stratigraphic classification was in close agreement with the combined well log analysis. Structural and stratigraphic interpretation of the NE-SW oriented seismic reflection sections Line\_13 and its perpendicular NW-SE oriented seismic Line\_5 (Figure 12) confirmed the four seismic stratigraphic horizons representing the bases of Bima Formation, Gongila Formation, Fika Formation and Chad Formation.

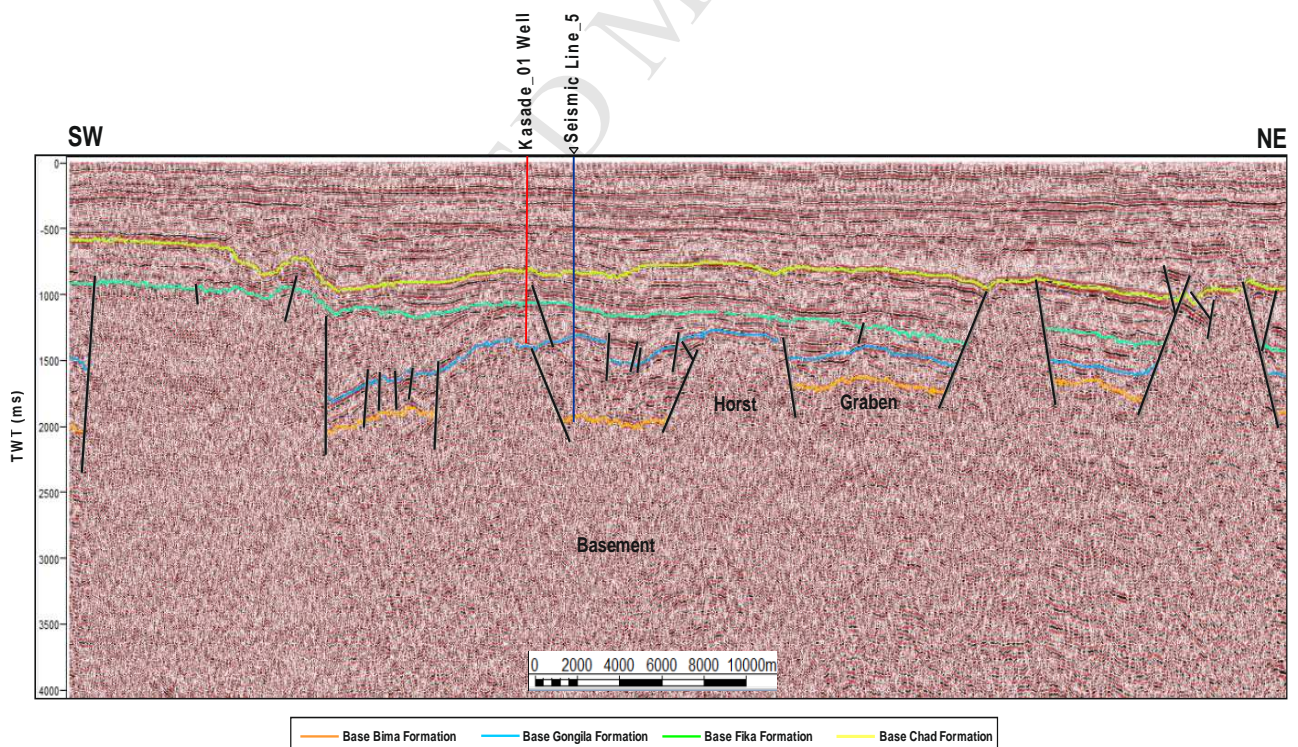
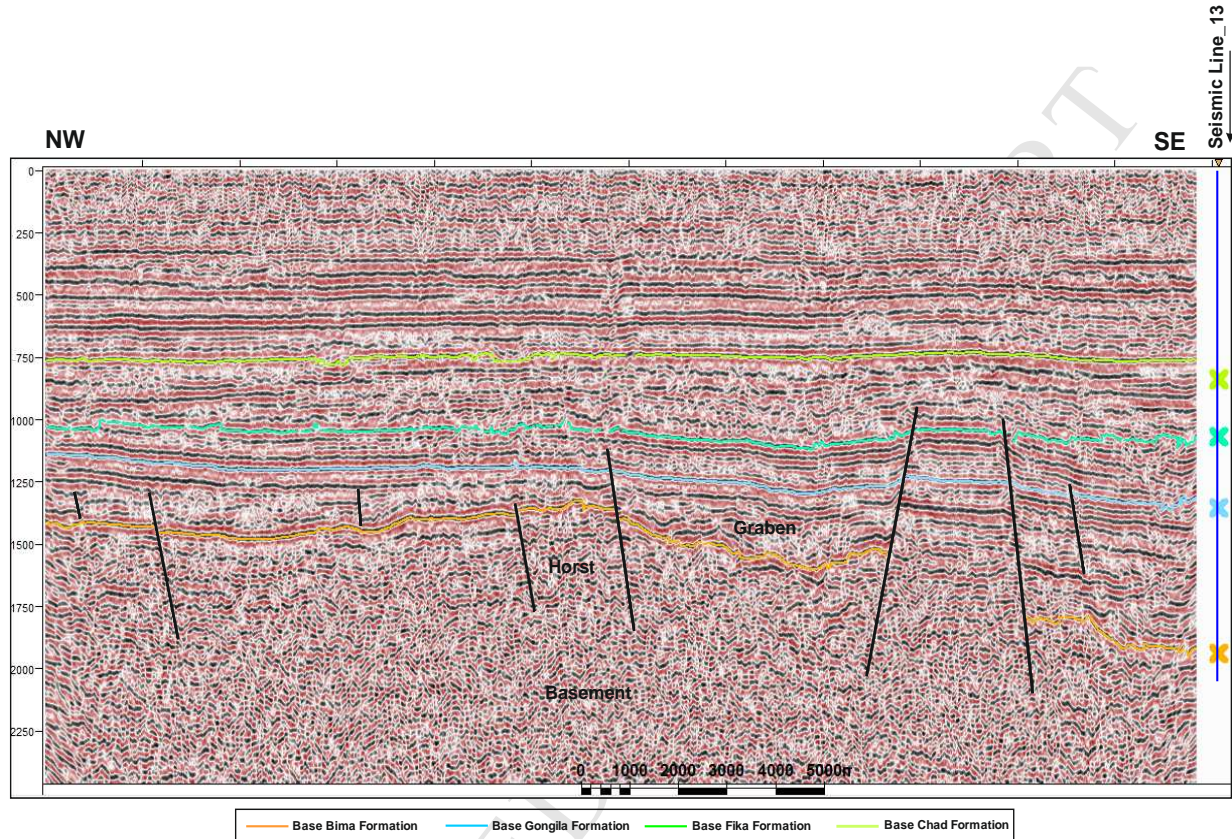


Figure 11. Interpreted NE-SW oriented seismic Line\_13 showing stratigraphic horizons correlated from the well logs. Subsurface basin structure indicating horst and graben features with Kasade\_01 (KAS) well bottomed on horst and basal facies infilled within grabens.

582 The position of correlated Kasade\_01 (KAS) well as indicated on the interpreted seismic  
 583 section (Figure 11) revealed that the well was bottomed at the top of a subsurface horst  
 584 feature, which confirmed findings from N-S well logs cross section interpretation in Figure  
 585 7a.



586  
 587  
 588 Figure 12. Interpreted NW-SE oriented seismic Line\_5 which perpendicular bisects seismic Line\_13 as shown in Figure 6.  
 589 Relative positions of the mapped seismic stratigraphic horizons from intersecting seismic line\_13 are shown on the right.

590  
 591 The Cretaceous basin morphology consists of fault lineaments which form half-graben  
 592 and graben-and-horst architecture made up of several high angle normal faults affecting  
 593 mainly the basal units. The basement topography reflected the Cretaceous tectonic and rift  
 594 evolution of the basin, which controlled the deposition of the basal facies. Relatively  
 595 shallower depths in the south-western and north-eastern parts exist between a much deeper  
 596 basin depocenter. Base of the Aptian – Albian is delineated by sub-parallel attenuated weak –  
 597 moderate amplitude reflector of the basal Bima Formation deposited within the grabens or  
 598 faulted troughs separated by horsts, which controlled the facies distribution in the Bima,  
 599 Gongila and Fika Formations. The base of Bima Formation terminated discordantly at the  
 600 bottom flanks of the igneous bodies while having a concordant depositional relationship with  
 601 the overlying seismic facies units. Internal seismic facies in Bima Formation is characterised



by weak uneven amplitude reflectors distributed within the grabens. The overlying base of the Gongila Formation is characterised by sub-parallel to parallel configurations of stronger seismic reflectors marking the top of deeper horst faults mostly developed in the deeper basin depocenter and truncated at the lower flanks of the shallower horst faults. The seismic reflector representing the base of Fika Formation is characterised by strong and uneven configuration best developed in the south-western part of the area where it is folded and marked the top of the main shallow horst feature mapped in the seismic section. However, the Fika Formation was truncated at the middle of the horst and graben fault flanks in the north-eastern sector of the area (Figure 11). Concordant relationship exists between the Fika Formation and the strongest seismic reflectors which characterised the overlying Chad Formation which has continuous parallel amplitude reflections representing base of the Chad Formation. The characteristic strong seismic reflection is best developed in the north-eastern sector of the area where it marked the thickest seismic facies towards the Lake Chad as shown in (Figure 11). Medium and small scale observations within the Chad Formation indicate potential sequences and parasequences as represented by strong and continuous reflections across the entire area. The seismic analysis shows that the top portion of the Chad Formation is relatively unaffected with faulting and folding in comparison with its base that appeared folded due to the effect of shallow subsurface horst features.

## 5 Discussion

This study utilised existing well log and 2-D seismic data for the north-eastern Bornu Basin adjoining the Lake Chad that were used variously by several workers to study the subsurface stratigraphy of the basin. However, most previous studies used segregated ditch cutting samples obtained from few wells. Nonetheless, this study confirmed findings from previous works including Okosun, (1995a); Olugbemiro et al. (1997); Obaje et al., (2004a), Moumouni et al., (2007); Obaje, (2009), variously used ditch cuttings from few wells and suggested the non-occurrence of Gombe Formation and Kerri-Kerri Formations in the north-eastern part of the basin. The present study thus support the existence of four stratigraphic units including Bima, Gongila, Fika and Chad Formations in the north-eastern part of the Bornu Basin as penetrated by the 23 wells. Probably due to the lack of surface outcrops in the north-eastern part of the basin many workers generalised the geology of the adjoining Gongola Basin in the Upper Benue Trough to include the entire parts of the Bornu Basin as suggested by Adepelumi et al., (2012); Avbovbo et al., (1986); Hamza and Hamidu, (2012).

The generalisation was probably due to the existence of Gombe Formation and Kerri-Kerri Formation in the southern part of the basin extending from the Gongola Basin in the southern boundary. Miller et al., (1968) and Burke, (1976) initially suggested that Kerri-Kerri Formation which directly underlies the Chad Formation as well as the subsequent underlying Gombe Formation found in other parts of the basin terminated at Maiduguri area of the basin and have not extended to the Lake Chad area in the north-eastern part. Well sections, which showed the uppermost Chad Formation as the thickest layer was also indicated on seismic sections having strong seismic reflections representing possible sequences and parasequences (Figure 11 & 12). This supports the findings that the Chad Formation is subdivided into upper, middle and lower layers (Miller et al., 1963; Isiorho and Nkereuwem, 1996).

So far published stratigraphic studies of the basin using well log data analysis were few and inadequate. However, Adepelumi et al. (2012) used gamma ray and resistivity log data obtained from the wells and identified seven stratigraphic successions including an undefined Pre-Bima Formation, Gombe Formation and Kerri-Kerri Formation in the north-eastern area. Since rock outcrops in the area were widely reported as scarce, integrated study using several different datasets to validate findings were not carried out. The seven stratigraphic units in the north-eastern area as interpreted from by Avbovbo et al. (1986) and Olugbemiro and Oloronniwo (2010) used disjointed 2-D seismic data. In this study, well log and seismic data analyses have indicated stratigraphic successions in the basin including their depths, thicknesses and lateral variations. The CLP method which utilises combined well log data analysis, which is validated with seismic stratigraphic analysis have established the synergistic relationship between the different datasets.

The basin architecture and subsurface topography is revealed by the well log sections consisting of thicker depocenter or mini basin flanked by low relief areas (Figure 7 a, b). The depocenter is identified on the seismic sections as graben infilled controlled sedimentation. As indicated in the seismic Line\_13, Kasade\_01 (KAS) well was bottomed over a bulging horst feature, which accounts for the absence of the basal Bima Formation that was mainly deposited within grabens. The absence of Bima Formation in Kasade\_01 (KAS) well and Bulte\_01 (BUT) well is because the wells bottomed over basement horst features and have not penetrated the basal Bima Formation. Fault lineaments mapped in the intersecting seismic sections indicate two main structural trends consisting of NNW-SSE trending lineaments observed on the NE-SW oriented seismic Line\_13 and the NE-SW trending lineaments on the NW-SE oriented seismic Line\_5. The correlated well log interpretation has identified

environments of deposition for the subsurface facies units in the north-eastern Bornu Basin, which generally agrees with the inferences by Okpikoro and Olorunniwo (2010).

Although intact rock core samples provide direct physical contact with the subsurface lithology, well log data provide continuous indirect digital in-situ record of the subsurface than cannot be obtained from drilling and sampling. Similarly well log data provide more reliable continuous in-situ rock record than segregated and disturbed samples of ditch cuttings used by previous workers in the basin for more accurate stratigraphic reconstruction. The CLP method compare corresponding responses at same depths in order to increase facies predictability and improve reliability of the correlation. The stratigraphy of the north-eastern Bornu Basin in this study relied on the background knowledge of the general stratigraphy of the basin obtained from outcrop, core and cuttings.

## 6 Conclusions

The present study, which utilised new combined data analysis, has provided a detailed stratigraphic interpretation of the available subsurface data for the north-eastern part of the Bornu Basin. The local stratigraphy of the north eastern area is constrained within the general context of sedimentary deposition in the Bornu Basin. The study provided alternative method for stratigraphic studies in the Bornu Basin characterised by flat topography and lack of bedrock outcrops that made previous studies often generalised and therefore inadequate. Stratigraphic facies interpretation using cores and outcrop data often affected by completeness of sections are most likely subjected to generalisation. However, subsurface facies characterisation from well log data allows for enhanced correlation of inferred strata from continuous data. This study has demonstrated the accuracy of data correlation and supports the objective of multi-source data integration. The following is specifically concluded:

- Four stratigraphic units consisting of Bima Formation, Gongila Formation, Fika Formation and Chad Formation exist in the north-eastern part of the Bornu. Gombe Formation and Kerri-Kerri Formation were not deposited in the north eastern Bornu Basin.
- The stacking patterns of individual sedimentary formations were deduced from the combined well log analysis. Bima Formation and Fika Formation were characterised by aggradational stacking pattern. Gongila Formation is characterised by

progradational stacking pattern. Fika Formation is characterised by retrogradational stacking pattern.

- Subsurface thickness variation in the north-eastern Bornu Basin revealed distinct infill pattern of the formations forming a central depocenter or mini basin flanked by shallower depth depositional centres.
- The depositional pattern in the area was controlled by the basement tectonic features forming horst and graben and associated faults which originated from the Cretaceous rifting and basin evolution. The basal Bima Formation was deposited in the grabens and terminated at the flanks of the graben faults while the overlying formations are relatively unaffected by tectonic structures.
- The uppermost Chad Formation represents the thickest in the north eastern area and supports the existence of sequences representing further stratigraphic subdivisions within the formation.
- The thickness of Chad Formation increases eastward towards the Lake Chad.
- The close agreement in the two-way-time velocities in the sonic log and the seismic data correlation proved the synergistic relationship between the different data sets.
- Synergistic analysis of multiple logs herein presented provides more reliable interpretation of the available well log data.
- This comprehensive study using combined multiple subsurface data analysis provides a reliable validation of the local stratigraphy in the north-eastern part of Bornu Basin since the area is characterised by thick sediment cover and devoid of continuous bedrock outcrops necessary for any useful field geological mapping.
- The effectiveness of the proposed CLP method is based on the synergistic relationship between the various physical properties measured by the different logging methods. The new method has demonstrated that use of multiple log types increase the reliability of well log analysis for geological interpretation than using any one or two types of well log.

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## References

- Abdelsalam, M. G., Robinson, C., Elgaz, F., & Stem, R. J. (2000). Applications of Orbital Imaging Radar for Geologic Studies in Arid Regions: The Saharan Testimony. *Photogrammetric Engineering & Remote Sensing*, 66(6), 717-726.
- Abdullahi, A., Nassr, S., & Ghaleeb, A. (2013). Remote sensing and geographic information system for fault segments mapping a study from Taiz area Yemen. *Journal of Geological Research*, 1-16.
- Adegoke, A. K., Abdullah, W. H., Hakimi, M. H., & Yandoka, B. M. (2014). Geochemical characterisation of Fika Formation in the Chad (Bornu) Basin, northeastern Nigeria: Implications for depositional environment and tectonic setting. *Applied Geochemistry*, 43, 1 - 12.
- Adeigbe, O. C., & Abimbola, A. F. (2013). The Cretaceous - Tertiary clastic rocks weathering indices: A case study of Maastrichtian? - Paleocene rock succession, Bornu Basin, Northeastern Nigeria. *International Journal of Engineering Sciences and Research Technology*, 2(2), 122 - 130.
- Adepelumi, A. A., Alao, O. A., Ako, B. D., & Oseikpe, R. E. (2012). Modeling of Hydrocarbon Potential And Thermal Maturity of Gongila Shale Chad Basin, Northeastern Nigeria. *Oil Shale*, 29(2), 151-172.
- Ajayi, C. O., & Ajakaiye, D. E. (1981). The Origin and Peculiarities of the Nigeria Benue Trough. Another look from recent gravity data obtained from middle Benue. *Tectonophysics*, 286-329.
- Alalade, B., & Tyson, R. V. (2010). Hydrocarbon Potential Of The Late Cretaceous Gongila And Fika Formations, Bornu (Chad) Basin, Ne Nigeria. *Journal of Petroleum Geology*, 33(4), 339-353.
- Anakwuba, E., & Chinwuko, A. (2012). Re-Evaluation of Hydrocarbon Potentials of Eastern Part of the Chad Basin, Nigeria: An Aeromagnetic Approach. *AAPG Annual Convention and Exhibition*, Long Beach, California: AAPG.
- Asquith, G. B., & Gibson, C. R. (1982). *Basic well log analysis for geologists American Association of Petroleum Geologists, Methods in Exploration Series*.
- Avbovbo, A., Ayoola, E., & Osahon, G. (1986). Depositional and structural styles in Chad Basin of northeastern Nigeria. *AAPG Bulletin*, 70, 1787-1798.
- Benkhelil, J. (1988). Structure et evolution geodynamique du bassin intracontinental de la Benoue, Nigeria. *Bull. Cent. Rech. Explor. Prod., Elf-Aquitaine*, 2(1), 29-128.
- Binks, R. M., & Fairhead, J. D. (1992). A plate tectonic setting for Mesozoic rifts of West and Central Africa. *Tectonophysics*, 213, 141-151.

- Boboye, O. A., & Abimbola, A. F. (2009). Hydrocarbon Potential of the Lithostratigraphic Units in Late Cenomanian-Early Paleocene Shale, Southwestern Chad Basin. *World Applied Sciences Journal*, 7(5), 567-573.
- Boboye, O., & Akaegbobi, I. (2012). Sedimentological and Palyno-environmental appraisal of the late quaternary sediments, north-eastern Bornu Basin. *Quaternary International*, 262(7), 14–19.
- Bueno, J. F., Honório, B. C., Kuroda, M. C., Vidal, A. C., & Leite, E. P. (2014). Structural and stratigraphic feature delineation and facies distribution using seismic attributes and well log analysis applied to a Brazilian carbonate field. *Interpretation*, SA83 - SA92.
- Burke, K., Dessauvage, T. F. J., Whiteman, A. J. (1971). Opening of the Gulf of Guinea and Geological History of the Benue Depression and Niger Delta. *Nature Physical Science*. 233.
- Burke, K. (1976). The Chad Basin: An active intra-continental basin. *Tectonophysics*, 36(1-3), 197–206.
- Carmouze, J. P. (1983). Hydrochemical Regulation of the Lake: in Lake Chad ecology and productivity of shallow tropical system. 95-123.
- Carter, J. D. (1964). *Geological Map of Nigeria, 1:2000,000*. Geological Survey Nigeria.
- Carter, J., Barber, W., & Jones, G. (1963). The geology of parts of Adamawa, Bauchi and Bornu provinces in northeastern Nigeria. *Geol. Surv. Nigeria Bull* 30.
- Chinwuko, A. I., Onwuemesi, A. G., Anakwuba, E. K., Onuba, L. O., & Nwokeabia, N. .. (2012). Interpretation of Aeromagnetic Anomalies over parts of Upper Benue Trough and Southern Chad Basin, Nigeria. *Advances in Applied Science Research*, 3(3), 1757-1766.
- Cratchley, C. R., & Jones, G. P. (1965). An interpretation of the Geology and gravity anomalies of the Benue Valley, Nigeria. *Overseas Geol. Surv. Geophys. Paper*, 1.
- Cratchley, C., Louis, P., & Ajakaiye, D. (1984). Geophysical and geological evidence for the Benue Chad Basin Cretaceous rift valley system and its tectonic implications. *Journal of African Earth Sciences*, 2(2), 141-150.
- Dou, L., Xiao, K., Cheng, D., Shi, B. and Li, Z. (2007). Petroleum geology of the Melut basin and the great Palogue field, Sudan. *Marine and Petroleum Geology*, 24 (3), Elsevier BV, p.129–144.
- Ellis, D. V., & Singer, J. M. (2007). *Well logging for Earth Scientists* (2nd ed.). The Netherlands: Springer.



- 802 Gardner, G., Gardner, L., & Gregory, A. (1974). Formation velocity and density - the  
803 diagnostic basics for stratigraphic traps. *Geophysics*, 39, 770-780.
- 804 Genik, G. (1992). Regional framework, structural and petroleum aspects of rift basins in  
805 Niger, Chad and the Central African Republic. *Tectonophysics*, 213, 169-185.
- 806 Genik, G. J. (1993). Petroleum geology of cretaceous-tertiary rift basins in Niger, Chad and  
807 CAR. *American Association of Petroleum Geologists Bulletin*, 77(8), 1405-1434.
- 808 Grant, N. K. (1971). The South Atlantic, Benue Trough and Gulf of Guinea Cretaceous. *Bull.*  
809 *geol. Soc. Am.*, 82, 2295-8.
- 810 Hamza, I., & Hamidu, I. (2012). Hydrocarbon resource potential of the Bornu basin  
811 northeastern Nigeria. *Global Journal of Geological Sciences*, 10(1).
- 812 Herron, D. A. (2011). *First steps in seismic interpretation: SEG, Geophysical Monograph*  
813 *Series, no. 16*. Tulsa Oklahoma.
- 814 Herron, D. A. (2014). Tutorial: Tying a well to seismic using a blocked sonic log.  
815 *Interpretation*, SD1-SD7.
- 816 Igbokwe, O. A. (2011). *Stratigraphic Interpretation of Well-Log data of the Athabasca Oil*  
817 *Sands Alberta Canada through Pattern recognition and Artificial Intelligence*.  
818 Unpublished MSc Thesis Westfälische Wilhelms-Universität Münster (WWU)  
819 Institute for Geoinformatics (ifgi), Münster Germany.
- 820 Isiorho, S. A., & Matisoff, G. (1990). Groundwater recharge from Lake Chad. *Limnology and*  
821 *Oceanography*, 35(4), 931-038.
- 822 Isiorho, S. A., & Nkereuwem, T. O. (1996). Reconnaissance Study of the Relationship  
823 Between Lineaments and Fractures in the Southwest Portion of the Lake Chad Basin.  
824 *Journal of Environmental and Engineering Geophysics*, 1(1), 47-54.
- 825 Kassenaar, J. D. (1989). *Automated Classification Of Geophysical Well Logs*. Unpublished  
826 MSc Thesis University of Waterloo, Ontario Canada. Retrieved from  
827 [ftp://earthfx.com/software/vlw3/brochure/MultiWell%20Papers/Kassenaar%20Thesis.](ftp://earthfx.com/software/vlw3/brochure/MultiWell%20Papers/Kassenaar%20Thesis.pdf)  
828 pdf
- 829 Kenneth, H., & Alan, H. (2003). *Interpretation of Shaly Sands*. Retrieved from Dialog:  
830 [http://www.lps.org.uk/docs/heslop\\_shaly\\_sands.pdf](http://www.lps.org.uk/docs/heslop_shaly_sands.pdf)
- 831 Krassay, A. A. (1998). Outcrop and drill core gamma-ray logging integrated with sequence  
832 stratigraphy: examples from Proterozoic sedimentary successions of northern  
833 Australia. *AGSO Journal of Australian Geology & Geophysics*, 17(4), 285-299.
- 834 Madibboyina, J. C., & Rao, N. (2011). Subsurface facies analysis using electrologs - A case  
835 study on Krishna Godavari Basin Rajahmundry. *The 2nd South Asian Geoscience*  
836 *Conference and Exhibition, GEOIndia2011*. New Delhi.

- 837 Miller, R. E., Johnson, R. H., Olowu, J. A., & Uzoma, J. U. (1968). *Groundwater Hydrology*  
838 *of the Chad Basin in Bornu and Dikwa Emirates, Northeastern Nigeria with special*  
839 *emphasis to the flow life of the Artesian system.* United States geological survey  
840 water supply paper 1757-1.
- 841 Moumouni, A., Obaje, N. G., Chaanda, M., & Goki, N. (2007). Geochemical evaluation of  
842 the hydrocarbon prospects in the Nigerian sector of the Chad Basin. *Petroleum*  
843 *Science Research Progress*, 1-12.
- 844 Obaje, N. G. (2009). *Geology and Mineral Resources of Nigeria* (Vol. 120). Springer.
- 845 Obaje, N. G., Wehner, H., Hamza, H., & Scheeder, G. (2004). New geochemical data from  
846 the Nigerian Sector of the Chad Basin: Implications on hydrocarbon prospectivity.  
847 *Journal of African Earth Sciences*, 38, 477-487.
- 848 Okosun, E. (1995a). Review of the Geology of Borno Basin. *Journal Mining and Geology*,  
849 21, 113-122.
- 850 Okpikoro, F., & Olorunniwo, M. (2010). Seismic Sequence Architecture And Structural  
851 Analysis of Northeastern Nigeria Chad (Bornu) Basin. *Continental J. Earth Sciences*,  
852 5(2), 1-9.
- 853 Olade, M. A. (1975). Evolution of Nigeria's Benue Trough (Aulacogen): a tectonic model.  
854 *Geol. Mag*, 112(6), 575-583.
- 855 Olugbemiro, O. R. (1997). *Hydrocarbon potential, maturation and palaeoenvironments of*  
856 *the Cretaceous (Cenomanian to Santonian) series in the Bornu (Chad) Basin, NE*  
857 *Nigeria Published Ph.D. Dissertation.* (Vol. 14). Tuebingen: Mikropalaeontologische  
858 Mttalungen.
- 859 Olugbemiro, R. O., Ligouis, B., & Abaa, S. I. (1997). The Cretaceous Series In The Chad  
860 Basin, Ne Nigeria: Source Rock Potential and Thermal Maturity. *Journal of Petroleum*  
861 *Geology*, 20(1), 51-68.
- 862 Peterson, J. A. (1985). *Geology and petroleum resources of central and east-central Africa*  
863 *Open-File Report 85-589.* Missoula, Montana: United States Department of the  
864 Interior Geological Survey. [Online]. Available at:  
865 <http://pubs.usgs.gov/of/1985/0589/plate-4.pdf> [Accessed: 6 May 2016].
- 866 Peters, S. W. (1978). Stratigraphic Evolution of the Benue Trough and its implication for the  
867 Upper Cretaceous Paleogeography of West Africa. *Journal of Geology*, 78, 311 – 312.
- 868 Petters, S. W., & Ekweozor, C. M. (1982). Petroleum Geology of Benue Trough and  
869 Southeastern Chad Basin, Nigeria. *AAPG Bulletin*, 66, 1141-1149.
- 870 Popoff, M., Benkhelil, J., Simon, B., & Motte, J. (1983). Approche geodynamique du fosse  
871 de la Benoue (N. Nigeria) a partir des donnees de terrain et de teledetection. *Bull.*  
872 *Cent. Rech. Expl. Prod., Elf-Aquitaine, Pau, France*, 7, 323-337.

- 873 Railsback, L. B. (2011). Synthetic log responses to lithologies. Retrieved from  
874 [www.gly.uga.edu/railsback\\_11111figs\\_8180ExampleLog\\_pdf.pdf](http://www.gly.uga.edu/railsback_11111figs_8180ExampleLog_pdf.pdf)
- 875 Schaefer, A. (2005). *Klastische Sedimente*. Elsevier, Spektrum Akad. Verl.
- 876 Umar, T. (1999). *Geologie petroliere du secteur Nigerian du basin du Lac Tchad*.  
877 *Unpublished Ph.D. Dissertation. Universite de pau et des pays de l' adour. Centre*  
878 *Universitaire de Recherche Scientifique Laboratoire de Geodynamique et*  
879 *Modelisation des Bassins Sedimentaires:.*
- 880 Zaborski, P., Ugodulunwa, F., Idornigie, A., Nnabo, P., & Ibe, K. (1997). Stratigraphy and  
881 structure of the Cretaceous Gongola Basin, northeastern Nigeria. *Bulletin des Centres*  
882 *de Recherches Exploration-Production Elf-Aquitaine*, 153–185.
- 883

**Highlights:**

- A Combined Log Pattern method for well log analysis is presented.
- Synergy between multiple well log and seismic datasets for structure and stratigraphic study is established.
- Combined qualitative and quantitative analysis for subsurface structure and stratigraphic study originally carried out in the Bornu Basin.
- Deposition in Bornu Basin was controlled by horst and graben system.
- Gombe Formation and Kerri-Kerri Formation were not deposited in the north-eastern Bornu Basin.